

Advanced stormwater treatment – comparison of technologies

Jes Vollertsen¹, Kenn H. Lange², Jan Pedersen², Per Hallager³, Annette Brink-Kjær³, Anne Laustsen⁴, Vibeke W. Bundesen⁴, Hans Brix⁵, Carlos Arias⁵, Asbjørn H. Nielsen¹, Nanna H. Nielsen⁶, Tove Wium-Andersen¹ and Thorkild Hvitved-Jacobsen¹

1) Aalborg University, Section of Environmental Engineering, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark

2) Municipality of Silkeborg, Public Utilities, Tietgensvej 3, 8600 Silkeborg, Denmark

3) Odense Water Ltd. Vandværksvej 7, 5000 Odense C, Denmark

4) Municipality of Aarhus, Water and Wastewater, Bautavej 1, 8210 Århus V

5) Aarhus University, Department of Biological Sciences, Ole Worms Alle 1, 8000 Aarhus C., Denmark

6) PH-Consult, Gladsaxevej 363, 2860 Søborg, Denmark

Abstract. In traditional wet ponds for stormwater management, the dissolved and colloidal bound pollutants are as a general rule only poorly removed. However, it is these fractions that are most mobile in the aquatic environment and which are most easily bio-accumulated. In the context of this project, different technologies for reducing dissolved pollutants and pollutants associated with fine particles and colloids were tested in full scale. For this purpose, 3 treatment facilities were constructed managing between 8.8 and 25.8 reduced ha. All facilities contained a wet detention pond and sand filters. In one facility the water from the sand filters was led through fixed media sorption filters. In another facility the pond bottom was enriched with iron salts. In the last facility aluminum was added to the incoming stormwater.

The treatment train consisting of wet detention pond, sand filter and sorption filter was efficient in reducing nutrients, heavy metals and PAHs. Accidently, the facility equipped with this treatment train received extremely high concentrations of copper and other heavy metals, which were consistently reduced to very low levels, proving an efficient safeguard against those pollutants. The treatment train consisting of wet detention pond with iron enriched bottom sediments followed by a sand filter and the treatment train consisting of aluminum addition to the stormwater entering the wet pond and followed by a sand filter, proved to be efficient in reducing suspended algae of the wet detention pond. Compared to the fixed media filters, the treatment trains were, however, less efficient with respect to removing heavy metals.

Introduction

Deterioration of receiving water bodies due to human development is a substantial environmental problem in many Nordic countries. The wish for improved aquatic environments has driven wastewater treatment towards low discharge concentrations and loads. Disregarding these efforts, many receiving waters continue to be of poor ecological quality. The reasons are many, but urban and highway stormwater discharges are often a significant part of the problem.

The need for treating stormwater runoff has therefore become widespread and various technologies for stormwater runoff treatment have been developed. A technology that in this context has proven itself effective and affordable is the concept of the wet detention pond, where a permanently wet pool is combined with a stormwater detention volume. A wet stormwater pond is intended for detention of the runoff water for sufficient time to allow treatment processes to proceed, and worldwide experiences have shown that well-designed wet detention ponds yield very good and stable pollutant reduction (Semadeni-Davies, 2006; Vollertsen et al., 2007).

The main treatment process in wet detention ponds is the removal of particles by sedimentation. The treatment concept is based on the fact that for many pollutants associated with stormwater runoff, most of the pollutant mass is associated with the particulate fraction. Other treatment processes, e.g. sorption and bioaccumulation, do also play a role. However, they are of minor importance in terms of pollutant mass removed.

When it comes to reduction of pollutants bound to colloidal or truly dissolved matter, wet detention ponds have rather limited effect. It is the dissolved and colloidal matter that is most mobile in the environment and which is most easily taken up by aquatic flora and fauna. It is therefore also this pollutant fraction that exhibits the most toxicity and potentially contributes most to the deterioration of the aquatic environment (Tuccillo, 2006). As a consequence hereof, wet detention ponds do only marginally reduce

stormwater toxicity and therefore do little to protect the aquatic environment towards stormwater toxicity (Marsalek et al., 1999; Wium-Andersen, in press).

A number of technologies to reduce the amount of dissolved and colloidal pollutants in stormwater have been assessed in the laboratory. However, full scale tests are few, and mostly poorly documented. In recognition hereof, 3 Danish municipalities and 2 Danish universities – financially supported by the European Commission and the Danish Environmental Protection Agency – have conducted a project where advanced stormwater treatment technologies for the reduction of dissolved and colloidal pollutants were tested in full scale. Three different technologies for advanced stormwater treatment were tested in this context: Sorption of dissolved pollutants in fixed-media sorption filters; Enrichment of pond bottom sediments with iron salts; Addition of aluminum salts to the incoming stormwater.

It is the objective of this paper to describe the technologies tested and the results obtained. Experiences with the operation of the technologies and the treatment effect towards a broad spectrum of pollutants is presented and discussed. Based on the obtained results, design criteria for different unit operations are discussed.

Methods

Three full-scale facilities were constructed to test and demonstrate the technologies for advanced treatment of stormwater runoff. One facility was constructed for each technology (Figure 1). All designs were based on traditional wet detention ponds as the first treatment step, and all designs contained sand filters to treat the outlet water. Three different sand filter layouts were tested: One horizontal sand filter, one sloping filter and one vertical filter. Details on the sand filter construction are presented in Vollertsen et al. (2009a) and characteristics of the 3 facilities are presented in Table 1.

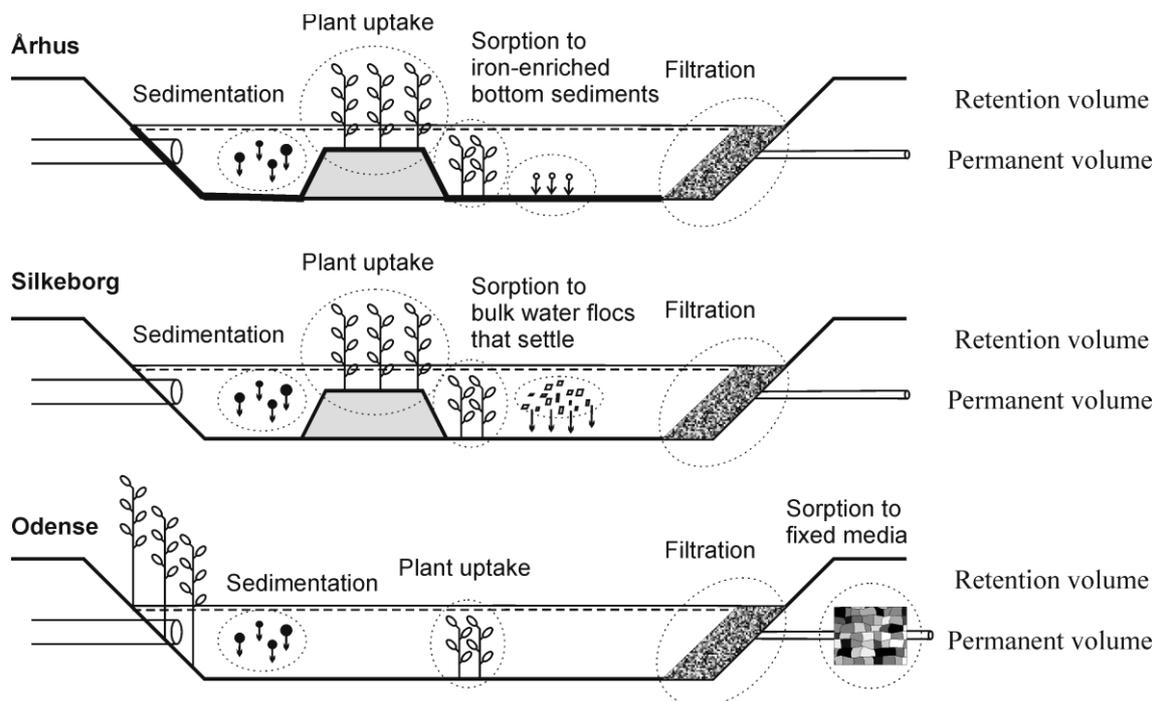


Figure 1 The principle layout of the 3 facilities for advanced stormwater treatment

The facility for testing fixed-media sorption (Odense) was taken into operation in February 2008. It consisted of a main filter filled with 55 m³ of Oyta Shells (Oytaco Ltd, Denmark), a natural product obtained from large deposits of fossil oyster shells in the shallow waters of the North Sea. The composition of the material was 96% CaCO₃ and MgCO₃ with a calcium content of 38%. The water drained through the sand filters and through the sorption filter by gravitation. In addition to the main filter, the facility was equipped with 3 test filters fed by intermittent pumping. One held 2.5 m³ of Oyta Shells, another held 2.5 m³ of granulated olivine (Filtersil 2749 from North Cape Minerals, Norway). The last filter was constructed as a sandwich of 0.5 m³ of Oyta Shells as the bottom layer on top of which was

0.5 m³ of iron oxide coated olivine (Filtersil TOC from North Cape Minerals, Norway) and 1.5 m³ of Oyta Shells. The facility in Odense was planted with a mix of larger and smaller littoral helophytes on the banks and with *Phragmites australis* (common reed) on the sand filters.

Table 1 Characteristics of the 3 facilities for advanced stormwater treatment

Advanced treatment technology	Fixed-media sorption	Iron enrichment	Aluminum addition
Location	Odense	Århus	Silkeborg
Type of catchment	Light industry	Residential (blocks of flats)	Residential (detached houses) and highway
Annual precipitation	657 mm y ⁻¹	661 mm y ⁻¹	719 mm y ⁻¹
Total catchment area	27.4 ha	57.4 ha	21.5 ha
Impervious catchment area	11.4 ha	25.8 ha	8.8 ha
Permanent wet volume	1,990 m ³	6,900 m ³	2,680 m ³
Retention volume	1,300 m ³	1,400 m ³	3,230 m ³
Permanent water depth, max	1.45	1.25	1.0
Area of horizontal sand filter	100 m ²	400 m ²	180 m ²
Length of sloping sand filter ¹	30 m	65 m	30 m
Length of vertical sand filter ²	6.3 m	12.6 m	6.3 m

1) The slope of the sand filter was 1:5 and stretched to the maximum water level of the retention volume

2) The height sand filter was to the maximum water level of the retention volume

The facility for testing iron enrichment of bottom sediments (Århus) was taken into operation in January 2008. On April 2, 2009, a total of 3,000 kg of iron chloride/sulfate solution (PIX 118 from Kemira Water Danmark A/S) was added to the pond. The product contained 116 g Fe³⁺ kg⁻¹ in an acidic solution. The product was mixed with pond water and distributed on the water surface. For this purpose, water was pumped from the pond and mixed with product pumped from the product container. The mixture was then delivered to a pipe floating on the pond surface and repeatedly dragged across the surface. Hereby a fairly uniform distribution of the iron salt into the pond water and subsequently on the pond bottom was achieved. The banks of the facility in Århus were left unplanted but the sandfilter was planted with *Phragmites australis* (common reed). Three high grounds (polders) planted with *Schoenoplectus lacustris* (Common Club-rush) were established in the pond to make the pond resemble the neighboring Lake Brabrand.

The facility for testing addition of aluminum to the stormwater (Silkeborg) was taken into operation in June 2008. The addition was achieved by flowproportional dosing of aluminum hydroxides/oxides to the incoming water (alumin_10 from Remondis Production GmbH). The product contained 155 g Al³⁺ kg⁻¹ in an alkaline solution. For every 10 m³ of inflow, a preset amount of the product was added to the inlet pipe of the pond. The addition of aluminum started on April 23, 2009 and varying amounts were added in the following period. During the first month of addition, a rather high concentration was added to the inflowing stormwater, namely a total of 17 kg Al to a total of 370 m³ of stormwater – i.e. in a concentration of 46 g Al m⁻³. This dose was then reduced to 5.2 g Al m⁻³ which was added from May 15 to September 21, during which the total inflow was 6,820 m³. The pond was subdivided into 3 compartments by earthen barriers in level with the permanent water surface. The banks of the facility were planted with a mix of larger and smaller littoral helophytes and the sand filters and the barriers with *Phragmites australis* (common reed).

Monitoring

All facilities were equipped with inlet flow measurement and measurement of the flow out from the sand filters. Each sand filter was monitored individually by full-flowing magnetic flow meters (Krohne Optiflux 2000) of identical size, i.e. 3 outlet flow meters per facility. The inlet flow was measured by 2 full-flowing magnetic flow meters (Krohne Optiflux 2000) of different size and an overflow weir. The measurement principle is outlined in Figure 2. The smaller magnetic flow meter measured flows down to 1 L s⁻¹ while the larger magnetic flow meter measured flows down to 10 L s⁻¹. The measurement by the small magnetic flow meter was used when the water level was below the overflow to the larger magnetic flow meter (Figure 2). When the flow passed the overflow weir, the sum of the measurement from the larger flow meter and the measurement from the overflow weir was used. The flow meters were protected against silting by a catch basin.

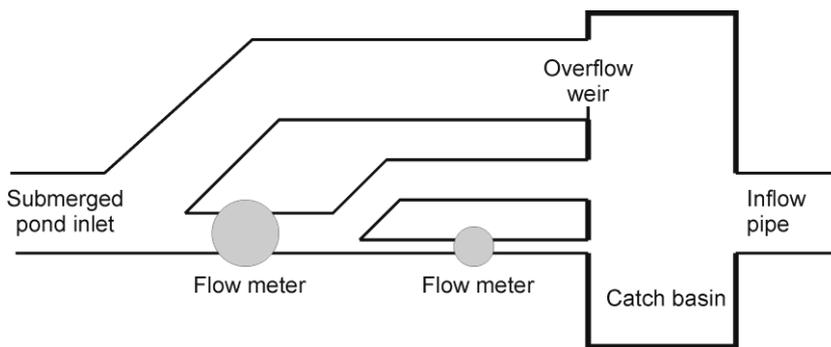


Figure 2 Inlet flow measurement

Water samples were collected from the inlet flow, the wet pond close to the sand filters, after the sand filters and – for the facility in Odense – after the fixed-media sorption filter. The inlet was sampled flow proportionally while the outlet was sampled time proportionally (MaxX TP4-C autosamplers). Originally it was planned to sample the outlet flow proportionally. However, the capacity of the sand filters was much lower than originally envisioned and the measurement of the outlet flow through the sand filters often below the detection level of the outlet flow meters. It was therefore deemed most appropriate to convert to time proportional sampling.

The samples were analyzed as mixed samples covering 2-3 weeks and analyzed by an accredited laboratory. Samples were analyzed by standard methods for lead, cadmium, chromium, copper, mercury, nickel, zinc, iron, aluminum, PAH after USEPA (16PAH), chlorophyll, total suspended solids (TSS), volatile suspended solids (VSS), total N, total P, orthophosphate (ortho-P), oil and fat, chloride, alkalinity and chemical oxygen demand (COD). Not all samples were analyzed for all parameters. Chlorophyll was measured on grab samples from the ponds. Total Coliform bacteria and E. Coli were determined on grab samples from the inlet to the facility in Århus.

The ponds were equipped with on-line sensors for pH (WTW SensoLyt 700 IQ), turbidity (WTW VisoTurb 700 IQ), dissolved oxygen (WTW FDO 700 IQ), temperature (via pH meter) and water level (Klay Hydrobar). Data from the sensors were stored every minute.

Results

The inflow to the 3 facilities differed significantly in quality (Table 2). In general terms, the runoff entering the facility in Silkeborg was the least polluted, followed by the runoff in Århus and Odense. At the facility in Odense, large amounts of dissolved heavy metals were present in the runoff. Especially copper, zinc and lead were found in high concentrations, most likely due to an illicit industrial discharge. The highest concentration of copper, zinc and lead in the runoff was $3,300 \text{ mg m}^{-3}$, $2,100 \text{ mg m}^{-3}$ and 110 mg m^{-3} , respectively. The maximum concentration of copper was more than 100 times higher than the maximum concentrations of the runoff water from the catchments in Silkeborg and Århus. Zinc and lead were about 10 times higher.

The runoff from the catchment in Århus was sporadically contaminated by wastewater containing fecal matter. At the inlet, wastewater odor could at times be found and grab samples from the inlet pipe showed up till 35,000 Total Coliform bacteria per 100 ml and 3.300 E. Coli per 100 ml. At other times the bacteria counts were zero.

Wet ponds

The pollutant removal by the ponds themselves is shown in Table 3 and was within the range typically reported for such facilities (e.g. Hvitved-Jacobsen et al, 1994; Vollertsen et al., 2007; Hvitved-Jacobsen et al., 2010). However, some anomalies were seen. The pond in Odense had comparatively poor treatment efficiency towards copper and zinc. The main part of these metals is typically associated with fine stormwater particles that settle out in wet ponds. However, in this case the metals were probably illicitly discharged to the stormwater system as dissolved or colloidal bound metals in rather high concentrations, resulting in poor removal efficiency. Another anomaly was seen in the pond in Århus, which consistently produced high concentrations of nickel while other metals were efficiently reduced. The reason is not

known, however, it seems likely that the nickel has been present in the natural soil minerals of the pond and slowly released to the bulk water. The facility in Silkeborg did also show a slight anomaly in terms of rather poor removal of zinc. The reason for this is not known but it could be the same as for nickel release at the facility in Århus.

Table 2 Concentrations of pollutants in the inlet to the facilities.

	Facility in Odense			Facility in Århus			Facility in Silkeborg		
	N	Average	St.Dev.	N	Average	St.Dev.	N	Average	St.Dev.
Lead [mg m ⁻³]	21	24.2	28.7	24	4.8	2.8	11	4.5	2.7
Cadmium [mg m ⁻³]	21	0.11	0.07	24	0.07	0.06	11	0.1	0.1
Chromium [mg m ⁻³]	21	5.6	3.7	24	4.4	2.6	11	2.2	1.5
Copper [mg m ⁻³]	21	469	770	24	20	10	11	15	5
Mercury [mg m ⁻³]	21	0.09	0.19	24	0.22	0.83	11	0.08	0.12
Nickel [mg m ⁻³]	21	29	40	24	7	5	11	9	3
Zinc [mg m ⁻³]	21	450	493	24	186	74	11	117	22
Iron [mg m ⁻³]	4	1608	730	21	1802	1031	2	870	325
Aluminum [mg m ⁻³]	3	950	550	3	1213	602	9	539	204
16PAH [mg m ⁻³]	15	0.45	0.51	14	0.43	0.41	3	0.13	0.22
TSS [g m ⁻³]	21	49	43	21	55	37	12	31	22
VSS [g m ⁻³]	4	37%	5%	5	52%	19%	-	-	-
Total N [g m ⁻³]	21	3.29	1.68	21	2.35	1.08	12	2.47	3.05
Total P [g m ⁻³]	21	0.319	0.221	21	0.277	0.164	12	0.222	0.375
Ortho-P [g m ⁻³]	21	0.131	0.157	21	0.122	0.121	12	0.105	0.281
Oil and fat [g m ⁻³]	20	1.75	1.37	21	1.05	0.86	1	<0.1	-
Chloride [g m ⁻³]	4	100	126	5	147	105	-	-	-
Alkalinity [mole m ⁻³]	4	1.28	0.50	5	4.66	2.49	-	-	-
COD [g m ⁻³]	4	42	6	5	101	50	-	-	-

Sand filters

The concentration of most of the pollutants was efficiently reduced by the sand filters (Table 4). The sand filters were especially efficient for reduction of the rather high concentrations of copper, lead and zinc at the facility in Odense. However, phosphorous was not reduced by the sand filters. At the facility in Århus, the sand filters actually increased the phosphorous concentration in terms of both total phosphorous and orthophosphate. Similarly did the concentration of nickel at the facility in Silkeborg increase dramatically by passing the sand filters. At the facility in Århus and Odense, the sand filters furthermore released significant amounts of iron oxides, causing about 2 and 7 g m⁻³ iron in the outlet from the sand filters, respectively. At the facility in Århus the iron release from the sand filters was monitored closely and a clear decrease in iron release was observed over time. This observation indicates that the sand filters over a year or two probably will have washed clean of dissolvable compounds.

Table 3 Average pollutant reduction by the wet ponds. For The facility in Århus and Silkeborg, only data up till start of iron/aluminum addition are included

	Facility in Odense			Facility in Århus			Facility in Silkeborg		
	Inlet	Outlet	Reduction	Inlet	Outlet	Reduction	Inlet	Outlet	Reduction
Lead [mg m ⁻³]	24.2	6.7	72%	4.7	0.5	90%	3.1	2.2	29%
Cadmium [mg m ⁻³]	0.11	0.06	47%	0.08	<0.05	-	0.07	<0.05	-
Chromium [mg m ⁻³]	5.6	1.2	78%	4.0	0.6	86%	1.7	0.5	69%
Copper [mg m ⁻³]	469	200	57%	19	3	86%	14	8	40%
Mercury [mg m ⁻³]	0.09	0.06	37%	0.30	<0.05	-	0.10	<0.05	-
Nickel [mg m ⁻³]	29	12	59%	8	21	-152%	10	2	80%
Zinc [mg m ⁻³]	450	272	39%	208	47	77%	125	104	17%
16PAH [mg m ⁻³]	0.45	0.13	72%	0.49	0.04	92%	-	0.05	-
TSS [g m ⁻³]	49	18	65%	48	6	88%	19	3	82%
Total N [g m ⁻³]	3.29	2.22	32%	2.11	0.85	60%	3.39	2.33	31%
Total P [g m ⁻³]	0.319	0.152	52%	0.268	0.068	74%	0.293	0.026	91%
Ortho-P [g m ⁻³]	0.131	0.046	65%	0.113	0.014	88%	0.176	<0.005	-
Oil and fat [g m ⁻³]	1.7	0.3	82%	1.0	1.1	-18%	-	0.7	-
COD [g m ⁻³]	42	22	47%	101	57	44%	-	45	-

The hydraulic capacity of the sand filters was significantly lower than had been envisioned during design. When designing the filters, it was assumed that the comparatively large wet pond would cause less

clogging of the filters compared to traditional infiltration basins and the filters were sized accordingly. It was furthermore assumed that the vertical filters would show little or no clogging, followed by the sloping filters and the horizontal filters clogging most. However, it turned out that all filters clogged more or less to the same extent and to a much higher degree than envisioned.

Table 4 Average pollutant reduction by the sand filters. For The facility in Århus and Silkeborg, only data up till start of iron/aluminum addition are included

	Odense			Århus			Silkeborg		
	Pond	After sandfilter	Reduction	Pond	After sandfilter	Reduction	Pond	After sandfilter	Reduction
Lead [mg m ⁻³]	6.7	0.4	94%	0.5	0.3	39%	2.2	0.6	72%
Cadmium [mg m ⁻³]	0.06	0.05	16%	<0.05	<0.05	-	<0.05	<0.05	-
Chromium [mg m ⁻³]	1.2	<0.5	-	0.6	<0.5	-	0.5	1.1	-112%
Copper [mg m ⁻³]	200	25	87%	3	2	33%	8	5	38%
Mercury [mg m ⁻³]	0.06	0.06	-3%	<0.05	0.10	-	<0.05	<0.05	-
Nickel [mg m ⁻³]	12	6	53%	21	10	53%	2	81	-4009%
Zinc [mg m ⁻³]	272	28	90%	47	20	57%	104	20	81%
16PAH [mg m ⁻³]	0.13	0.01	89%	0.04	0.01	64%	0.05	<0.01	-
TSS [g m ⁻³]	18	14	18%	6	6	-6%	3	3	18%
Total N [g m ⁻³]	2.22	1.30	41%	0.85	0.65	23%	2.33	0.58	75%
Total P [g m ⁻³]	0.152	0.175	-15%	0.068	0.171	-150%	0.026	0.019	28%
Ortho-P [g m ⁻³]	0.046	0.038	18%	0.014	0.019	-41%	<0.005	<0.005	-
Oil and fat [g m ⁻³]	0.3	0.2	48%	1.1	0.2	84%	0.7	0.2	77%
COD [g m ⁻³]	22	15	33%	57	26	54%	45	9	80%

The hydraulic capacity of the vertical sand filter and the sloping sand filter were most of the time below the detection limits of the flow meters. However, the outflow from the horizontal sand filter was measurable and was proportional to the water pressure on the filter surface (Figure 3). Even at still lower water levels than shown in Figure 3, the outflow continued to be proportional to the water pressure (data not shown). Assuming that the resistance to the flow lies in a thin clogging layer in the upper part of the sand filter, the flow out of the filter can be described by a simplified version of Darcy's law (Equation 1) (Rauch and Stegner, 1994).

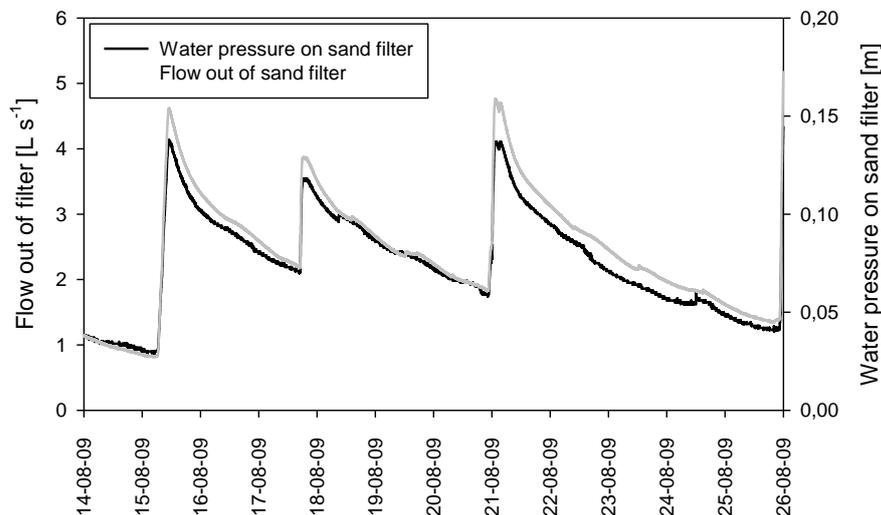


Figure 3 The relative water pressure on the horizontal sand filter and the corresponding outflow at the facility in Århus

$$Q = L \cdot A \cdot h \quad \text{Eq. 1}$$

Where Q is the flow through the clogging layer [m³ s⁻¹], L is a leakage constant [s⁻¹], A is the surface area and h is the water pressure at the clogging layer [m water column].

Analyzing the data shown in Figure 3 by means of Equation 1 yields a leakage factor, L , of $8.6 \cdot 10^{-5} \text{ s}^{-1}$. Applying this parameter in Equation 1 allows determination of the outflow at varying water depths and sand filter areas. E.g. for the sand filter of the facility in Århus from where the data originate, a water depth of 5 cm will give rise to 1.7 L s^{-1} of outflow, whereas a water depth of 50 cm will cause 17 L s^{-1} of outflow.

Sorption filters

The sorption filters effectively reduced the concentrations of copper, zinc, phosphorous and total solids (Table 5). The filters furthermore ensured that the extremely high concentrations of copper due to the illicit discharges came well below the water quality criterion for Danish fresh waters. In addition to polish the water quality of the stormwater runoff, the filters turned out to be an effective protection against pollutants which would otherwise have caused immediate toxic effects on the aquatic environment (Wium-Andersen et al., in press).

Table 5 Average pollutant reduction by the sorption filters at the facility in Odense

	After sand filter	After sorption filter	Reduction
Lead [mg m^{-3}]	0.4	0.6	-42%
Cadmium [mg m^{-3}]	0.05	<0.05	-
Chromium [mg m^{-3}]	<0.5	0.5	-
Copper [mg m^{-3}]	25	4	83%
Mercury [mg m^{-3}]	0.06	<0.05	-
Nickel [mg m^{-3}]	6	5	7%
Zinc [mg m^{-3}]	28	4	85%
16PAH [mg m^{-3}]	0.01	0.01	-3%
TSS [g m^{-3}]	14	4	72%
Total N [g m^{-3}]	1.30	1.08	17%
Total P [g m^{-3}]	0.175	0.025	86%
Ortho-P [g m^{-3}]	0.038	0.006	84%
Oil and fat [g m^{-3}]	0.2	0.1	21%
COD [g m^{-3}]	15	10	30%

Iron addition

The addition of the 3,000 kg of iron product to the wet pond in Århus took about 8 hours for 3 persons, i.e. it was rather labor-intensive. The added product was strongly acidic and caused the pH to drop below 4 for a few hours. However, some 10 hours after completion of the addition, the pH was up at 6.8 and after 2 weeks the pH was back at the same level as before the addition (between 8 and 9). During the addition the water became rust-red. However, the color disappeared within hours as the iron flocculated and precipitated. The addition caused algae and other particulates to flocculate and precipitate with the iron, and the water became visibly clearer.

The iron enrichment of the bottom sediments did not cause any measurable reduction in chemical water quality parameters. Actually, for a number of heavy metals the pond water concentrations increased compared to the time before the addition and the treatment efficiency of the pond itself deteriorated correspondingly. The product used for iron enrichment of the bottom sediments could, however, not have been the direct cause of the reduced treatment efficiency, as the product contained much less of the problematic metals than could be accounted for by the increased concentrations in the pond water. After the iron addition, nickel concentration in the pond doubled to 54 mg m^{-3} , i.e. around 8 times the inlet concentration. Other metals stayed consistently below the inlet concentrations. In principle, the addition could have caused the solution of bound heavy metals as the pH decreased. However, the conditions were only acidic for a few hours, and it seems therefore unlikely that the addition was the cause of the increased concentrations of heavy metals.

The treated water exiting the sand filters had similar heavy metals concentrations before and after the addition of iron to the pond. I.e. the sand filter reduced the increased concentrations of the pond water to the same and constant level stated in Table 4, indicating that the additional heavy metals present after the addition of iron to the pond were associated with suspended particles.

Even though the iron enrichment of the bottom sediments did not result in decreased concentrations of pollutants, it did counteract growth of algae in the pond (Figure 4). Compared to the pond in Odense, the

spring algae bloom was delayed and very much shortened and the chlorophyll content was low the rest of the summer.

Aluminum addition

The addition of aluminum to the stormwater runoff entering the facility in Silkeborg was much less labor intensive than the iron enrichment of the bottom sediments of the facility in Århus. The work was restricted to calibrating the dosing to the desired dosage level. As is seen from Figure 4, the dosing of aluminum was very effective to hinder algae blooms in the pond – more so than the iron enrichment of bottom sediments in Århus. However, when it came to chemical water quality parameters, no reduction could be seen. Actually, there was a slight increase in most heavy metal concentrations in the pond compared to before the addition. The difference in heavy metal concentrations from before the addition to during the addition was, however, not statistically significant. After passing the sand filters the water concentrations were similar to those before the aluminum addition.

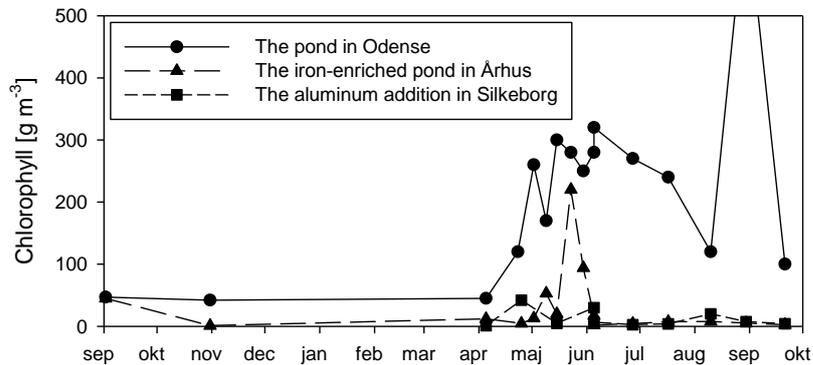


Figure 4 Chlorophyll in the three facilities. The bottom sediments of the pond in Århus were iron-enriched April 2, 2009. The aluminum addition to the stormwater entering the facility of Silkeborg was initialized April 23, 2009

Experiences and recommendations

The concept of wet stormwater ponds has once again proved to be efficient with respect to managing pollutants associated with particles, here amongst a significant fraction of heavy metals, phosphorous and PAHs (Table 3). A wet detention pond with a permanent water pool of 200-250 m³ (impervious ha)⁻¹ is under Danish climatic conditions an appropriate size, allowing good and efficient pollutant removal. The size of the retention volume has previously been shown to be of less importance for the pollutant removal and should be chosen based on the hydraulic capacity of the receiving waters (Vollertsen et al., 2009b).

Filtering of the water from the wet detention ponds through sand filters gave an added removal of many pollutants, but had less effect on others (Table 4). Phosphorous concentrations were for example not affected by the filters. In addition hereto were the sand filters prone to rapid clogging and had a limited hydraulic capacity – much more limited than was envisioned when designing the filters. How the capacity of the filters develops over time is not known. It is however most likely that it will decrease further, although the growth of the planted *Phragmites australis* may counteract clogging. Another issue was that the sand filters released iron which was clearly visible as ochre (hydrated iron oxide) flocculating in the water phase. The cause must have been that Fe(III) was contained in the sand, and reduced under anaerobic conditions in the filters. The formed Fe(II) was then released and subsequently reoxidized to Fe(III) in the presence of oxygen.

The lesson learned from the sand filters was therefore that these must be significantly larger than those constructed at the 3 facilities. The sand filters must furthermore not be allowed to become anaerobic, i.e. the filters must be drained. This means that a sand filter must be hydraulically separated from the wet pond and having the groundwater table at least 1-1½ m below the filter surface. This design approach will also give the filters a somewhat higher filter velocity as the hydraulic capacity of a drained sand is larger than that of an undrained sand. Most likely it will also to some extent counteract extensive clogging as the filters surface dries out between events. For such sand filters a long-term filter velocity of 1-1½ cm h⁻¹ at 5-50 cm ponding depths is likely to be a conservative value, which is also confirmed by

recommendations for stormwater infiltration ponds made by the US Environmental Protection Agency (US EPA, 2008). The grain-size distribution and the composition of the sand should also be considered. A coarser sand with a high uniformity coefficient might have a lower tendency to clog and hereby have a higher hydraulic capacity, and in a sand with less iron the problems with clogging as a consequence of precipitation of ochre might be less.

Sorption to fixed media of pollutants not managed by the sand filters was very efficient to further reduce pollutant concentrations (Table 5). Also for those pollutants that were present in comparatively high concentrations, the sorption filters consistently ensured low outlet concentrations. The reduction of a probably illicitly discharge of copper to the facility in Odense illustrates this well (Figure 5). As is seen from the figure, the treatment train consisting of wet pond, sand filter and sorption filter was an effective barrier protecting the receiving environment against the very high copper concentrations in the runoff. Sorption filters are, however, prone to clogging from compounds released from the sand filters – e.g. iron oxides. It seems therefore prudent to design the filters for a filter velocity similar to the sand filters. Such design is for example achieved by a sandwich construction of sand and filter media. Which filter media to apply and layered in which magnitudes is still uncertain, and further studies are needed in this context. However, the crushed oyster shells and the olivine applied in this study are definitely candidates as they are both effective and affordable.

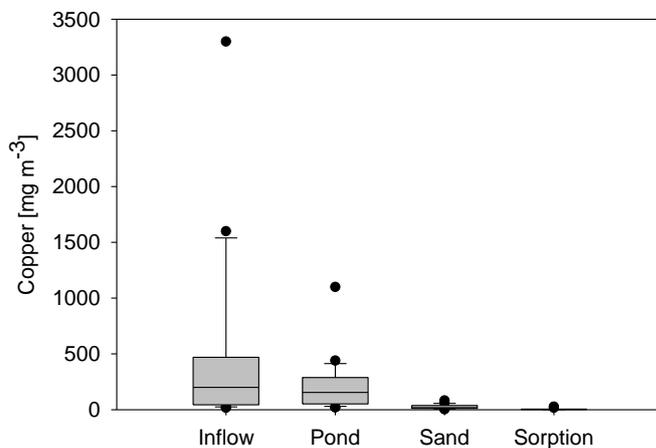


Figure 5 Removal of copper at the facility in Odense. The box shows the 25%, 50% and 75% percentiles, the error bars show the 10% and 90% percentiles and the full circles show outliers.

The addition of iron and aluminum salts did not cause any measurable reduction in pollutant concentrations. Certain heavy metals seemed even to have been removed less well after the addition of these chemicals. Whether this is an experimental artifact or a general issue is not known. However, both the iron enrichment of the bottom sediments and the aluminum addition to the incoming stormwater were effective in keeping algae concentrations low. The duration of the experiments did however not allow determining the optimal dosages. Further experiments are needed in this context.

The practical problems related to iron enrichment of bottom sediments seem prohibitive. Addition of either iron or aluminum to the incoming stormwater is, on the other hand, a rather simple technique which can be installed and automated. Whether iron salts or aluminum salts are the better agents and whether for example a continuous dosing of small amounts to all incoming water is preferable to fewer dosages at higher concentrations needs to be tested.

Conclusions

The treatment train consisting of a wet retention pond, a sand filter and a fixed media sorption filter was efficient in reducing dissolved and colloidal pollutants in the stormwater runoff. In the case of copper which in one of the catchments was present in extremely high concentrations, a reduction of better than 99% was seen and peak concentrations of several thousand microgram per liter were reduced to below the Danish water quality standard for fresh waters. The addition of aluminum and iron to the pond water did

efficiently manage algae blooms, ensuring low algae content of the pond water. It did, however, not reduce heavy metals and other pollutants present in the stormwater. The sand filters effectively polished the pond water to low discharge levels. However, the filters released iron oxides, probably due to anaerobic conditions in the sand. The hydraulic capacities of the filters were furthermore lower than had been envisioned, and in the range of traditional infiltration stormwater basins.

The results and experiences published in the present study demonstrate that advanced stormwater treatment applying comparatively low-tech technologies allow efficient pollutant management of the dissolved and colloidal fraction. Further investigations and full scale studies are however needed to optimize the design of the technologies.

Acknowledgements

This work has been supported by the LIFE financial instrument of the European Community (LIFE06 ENV/DK/000229).

References

- Hvitved-Jacobsen T, Johansen NB, Yousef YA (1994). Treatment systems for urban and highway run-off in Denmark. *The Science of the Total Environment*, 146/147: 499-506
- Hvitved-Jacobsen T, Vollertsen J, Nielsen AH (2010). *Urban and Highway Stormwater Pollution: Concepts and Engineering*. CRC Press, pp 544, ISBN: 9781439826850 (Publication Date: March 26, 2010)
- Le Coustumer S, Barraud S (2007). Long-term hydraulic and pollution retention performance of infiltration systems. *Water Science and Technology*, 55(4): 235–243
- Marsalek J, Rochfort Q, Mayer T, Servos M, Dutka B, Brownlee B (1999). Toxicity testing for controlling urban wet-weather pollution: advantages and limitations. *Urban Water*, 1(1): 91-103
- Rauch W, Stegner T (1994). The colmation of leaks in sewer systems during dry weather flow. *Water Sci. Technol.* 30 (1): 205–210.
- Semadeni-Davies A (2006). Winter performance of an urban stormwater pond in southern Sweden. *Hydrological Processes*, 20(1): 165-182
- Tuccillo ME (2006). Size fractionation of metals in runoff from residential and highway storm sewers. *Science of the Total Environment*, 355(1-3): 288-300
- US EPA (2008). National Pollutant Discharge Elimination System, National Menu of Stormwater Best Management Practices: <http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm>
- Vollertsen J, Åstebøl SO, Coward JE, Fageraas T, Madsen HI, Nielsen AH, Hvitved-Jacobsen T (2007). Monitoring and modeling the performance of a wet pond for treatment of highway runoff in cold climates. In: *Highway and Urban Environment. Alliance for Global Sustainability Bookseries Science and Technology: Tools for Sustainable Development*. G. M. Morrisson and S. Rauch (Editors). ISBN 978-1-4020-6009-0. Springer, The Netherlands, 499-509
- Vollertsen J, Lange KH, Pedersen J, Hallager P, Bruus A, Laustsen A, Bundesen VW, Brix H, Nielsen AH, Nielsen NH, Wium-Andersen T, Hvitved-Jacobsen T (2009a). Monitoring the startup of a wet detention pond equipped with sand filters and sorption filters. *Water Science and Technology*, 60(4): 1071-1079
- Vollertsen J, Åstebøl SO, Coward JE, Fageraas T, Nielsen AH, Hvitved-Jacobsen T (2009b). Performance and Modeling of a Highway Wet Detention Pond Designed for Cold Climate. Scheduled for publication *Water Quality Research Journal of Canada*, in 44(3)
- Wium-Andersen T, Nielsen AH, Hvitved-Jacobsen T, Vollertsen J (in press). Reduction of stormwater runoff toxicity by wet detention pond. In press for *Highway and Urban Environment*. Book Series: Alliance for Global Sustainability Series